



Improved modeling of geomagnetically induced currents in the South African power network

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[1] Geomagnetically induced currents (GICs), resulting from adverse space weather, have been demonstrated to cause damage to power transformers in the midlatitudes. There is growing concern over possible GIC effects in the Southern African network because of its long power lines. Previous efforts to model the electric field associated with GICs in South Africa have used a uniform ground conductivity model. In an effort to improve the modeling of GICs, GIC data together with the Hermanus Magnetic Observatory geomagnetic field data were used in order to obtain a multilayered ground conductivity structure. The method requires a definition of the network coefficients, which are then used in subsequent calculations. This study shows that GIC computed using the new network coefficients and the multilayered ground conductivity model improves the accuracy of GIC modeling. GIC statistics are then derived on the basis of the recordings of the geomagnetic field from 1996 to 2006 at Hermanus, the new network coefficients, and ground conductivity model. The geoelectric field was modeled using the plane wave method.

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1. Introduction

[2] Society today relies heavily on electricity in order to meet essential needs. To meet the rising demand for this energy, power companies require smooth and efficient delivery of services to the consumers. During the past 30 years many studies on geomagnetically induced currents (GICs) have been undertaken [e.g., Kappenman *et al.*, 1997; Boteler, 2001; Pirjola, 2002; Thomson *et al.*, 2005] in areas that have experienced problems in order to find a more economical means of preventing these space weather effects in man made technological systems.

[3] There is very little published data on GICs in the Southern African region because it was previously assumed that large GICs would be unlikely to occur in a low- to midlatitude region. However, there have been reports of transformer failures experienced during November 2003 at some substations following a series of geomagnetic

events in October and November of the same year as discussed by Gaunt and Coetzee [2007]. As well, there were broad studies by Koen [2002], who has investigated the reported cases of failures and started theoretical modeling of GICs in the Southern African power grid.

[4] Model calculations of GICs in a network depend on the fairly accurate determination of the geoelectric field and the network coefficients. Network coefficients are characteristics particular to each power transformer and power line and depend on the power system geometry and resistances [Viljanen and Pirjola, 1989, 1994]. A very important input for modeling the geoelectric field is the ground conductivity. The electric field is related to the magnetic field through the frequency-dependent surface impedance which contains information about the electrical properties of the underlying Earth structures [Simpson and Bahr, 2005].

[5] Previous efforts by Koen [2002] and Bernhardt [2006] to model GICs in South Africa used a uniform one layer ground conductivity structure following ideas proposed by Viljanen and Pirjola [1994] and Pulkkinen [2003]. Shortcomings in the uniform ground model can be compensated for by using a layered conductivity model that includes a wider frequency band associated with the GIC phenomena [Trichtchenko and Boteler, 2006; Pulkkinen *et al.*, 2007].

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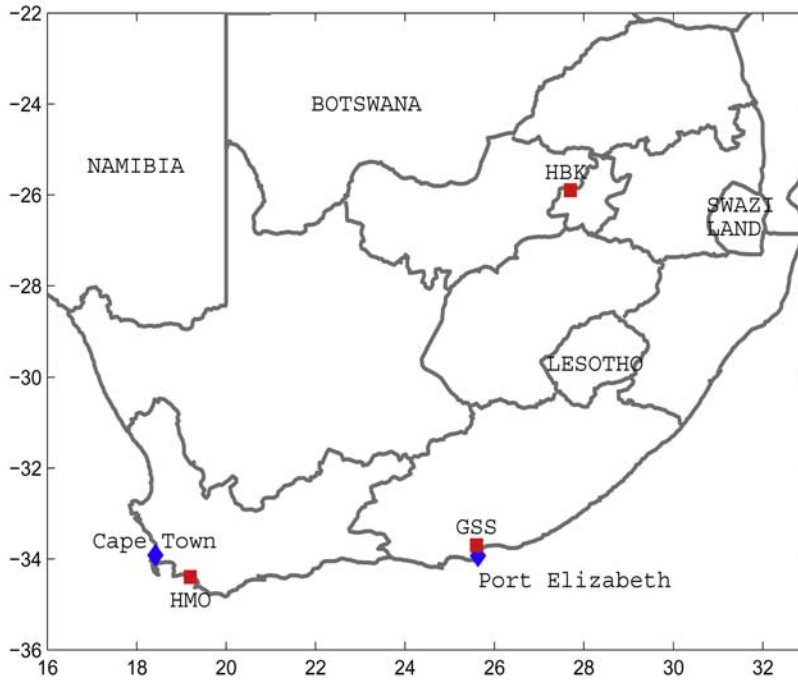


Figure 1. Map showing the positions (red squares) of geomagnetic observatories at Hermanus (HMO), Hartebeesthoek (HBK), and the Grassridge GIC substation site (GSS).

[6] Koen [2002] also used methods by Lehtinen and Pirjola [1985] to determine the network coefficients. This method requires a knowledge of the electrical power configuration, geometry and resistances (hereafter collectively called network parameters). In most cases, this information is not available and thus the task of updating the network coefficients as the network parameters change over time becomes almost impossible. However, Pulkkinen *et al.* [2007] have shown that measured GIC and geomagnetic field data can be used to update the network coefficients and that a knowledge of network parameters is not necessarily required.

[7] The aim of this study is to develop a conductivity model that improves the accuracy of GIC modeling by inclusion of a more realistic layered ground structure. This is important for the future development of a reliable and optimal GIC monitoring system for the South African power grid.

2. Data Sources

[8] The geomagnetic field data used in the study were obtained from the Hermanus Magnetic Observatory (34.4°S, 19.2°E) and were recorded using a three axis suspended FGE fluxgate magnetometer manufactured by the Danish Meteorological Institute. The horizontal components X and Y 1-min mean values for the storm of 29–31 October 2003 were used.

[9] GIC measurements were taken from the Grassridge electrical substation (33.7°S, 25.6°E) in South Africa. Mon-

itoring of GICs at Grassridge commenced in December 2001 under the EPRI Sunburst project. To aid our comparisons, 2-s data recorded at the Sun burst site was averaged to a 1-min sampling interval. Figure 1 depicts the positions of the two South African geomagnetic observatories at Hermanus and Hartebeesthoek (27.7°E, 25.9°S) with respect to the Grassridge Sunburst GIC site. Details of the network configuration were not available.

3. Determining the Network Coefficients

[10] Power network configurations change over time, which in turn will also change the network coefficients. To take this into consideration, a new set of network coefficients which are then used in subsequent calculations involving the multilayered conductivity model derivation have to be determined. Pulkkinen *et al.* [2007] have outlined a method which circumvents the complex process introduced by Lehtinen and Pirjola [1985] by using measured GIC and geomagnetic field data and where a knowledge of the network parameters is not necessarily required. Here, some steps involved in this method introduced by Pulkkinen *et al.* [2007] are highlighted.

[11] The relationship between the horizontal components of the geoelectric field $E_{x,y}$ and geomagnetic field $B_{x,y}$ is given in terms of the surface impedance by

$$E_{x,y}(\omega) = \pm \frac{Z}{\mu_0} B_{y,x}(\omega) + \varepsilon_1(\omega), \quad (1)$$

where $Z = Z(\omega)$ is the surface impedance, ω is the angular frequency, μ_0 is the permeability of free space and $\varepsilon_1(\omega)$ is the noise term. A 1-D case is assumed, so that only the off-diagonal terms of the surface impedance tensor can be used [Pulkkinen *et al.*, 2007, and references therein].

[12] It is further assumed that if we have a spatially constant electric field and the network coefficients are known, then GIC can be modeled in the spectral domain by the equation

$$\text{GIC}(\omega) = aE_x(\omega) + bE_y(\omega) + \varepsilon_2(\omega). \quad (2)$$

The quantities a and b are the network coefficients, specific to each transformer and power line, depending only on the resistance and geometrical composition of a power system [Viljanen and Pirjola, 1994].

[13] Expressing equation (2) in terms of equation (1) and considering the horizontal geomagnetic variations to be linear with respect to the x and y coordinate plane, we have

$$\tilde{\text{GIC}} = \frac{a}{\mu_0} \tilde{Z}\tilde{B}_y - \frac{b}{\mu_0} \tilde{Z}\tilde{B}_x + (a-b)\tilde{\varepsilon}_1 + \tilde{\varepsilon}_2, \quad (3)$$

so that the tilde sign depicts quantities in the spectral domain. Multiplying equation (3) by B_x^* and B_y^* yields

$$\tilde{\text{GIC}}\tilde{B}_x^* - \tilde{\varepsilon}\tilde{B}_x^* = \frac{a}{\mu_0} \tilde{Z}\tilde{B}_y\tilde{B}_x^* - \frac{b}{\mu_0} \tilde{Z}\tilde{B}_x\tilde{B}_x^* \quad (4)$$

$$\tilde{\text{GIC}}\tilde{B}_y^* - \tilde{\varepsilon}\tilde{B}_y^* = \frac{a}{\mu_0} \tilde{Z}\tilde{B}_y\tilde{B}_y^* - \frac{b}{\mu_0} \tilde{Z}\tilde{B}_x\tilde{B}_y^*, \quad (5)$$

with the asterisk denoting complex conjugate terms and $\tilde{\varepsilon}$ being the combined noise term. Solving equations (4) and (5) then gives

$$c \equiv \frac{b}{a} = \frac{\tilde{B}_y\tilde{B}_x^* - \chi|\tilde{B}_y|^2}{|\tilde{B}_x|^2 - \chi\tilde{B}_x\tilde{B}_y^*}, \quad (6)$$

where

$$\chi = \frac{\tilde{\text{GIC}}\tilde{B}_x^* - \tilde{\varepsilon}\tilde{B}_x^*}{\tilde{\text{GIC}}\tilde{B}_y^* - \tilde{\varepsilon}\tilde{B}_y^*}. \quad (7)$$

[14] The term c is independent of frequency and thus can be determined in the temporal domain by applying stationary conditions on the signal and later using the cross-correlation theorem [Pulkkinen *et al.*, 2007]. The ratio c can then be expressed as

$$c = \frac{\langle B_y B_x \rangle - \hat{\chi} \langle B_y B_y \rangle}{\langle B_x B_x \rangle - \hat{\chi} \langle B_x B_y \rangle}, \quad (8)$$

where

$$\hat{\chi} = \frac{\langle \text{GIC} B_x \rangle}{\langle \text{GIC} B_y \rangle}. \quad (9)$$

with the terms $\langle \dots \rangle$ used as a representation of the expectation values. Statistically, the noise term $\tilde{\varepsilon}$ is assumed to be independent of B_x and B_y and has a zero mean. Thus the terms containing the combined noise do not appear in equation (8) and (9). Pulkkinen *et al.* [2007] argued that even though this simplification may not always hold true, the methods applied in this case have been seen to improve the modeling accuracy of GICs. In any case, this process is much simpler than the full process applied in previous studies [e.g., Viljanen and Pirjola, 1994; Koen, 2002].

[15] Koen [2002] derived the network coefficients for Grassridge using the methods of Lehtinen and Pirjola [1985]. He modeled the GIC using a uniform resistivity of 1000 m with network coefficients $a = -80$ A km/V and $b = 15$ A km/V. We fixed first the value of the coefficient a to be that determined by Koen [2002] and then modified the coefficient b to agree with the ratio b/a as given in equation (6). Time derivatives of the geomagnetic field were used because of their characteristic shorter correlation time and approximately exponential decaying functional form [Pulkkinen *et al.*, 2007].

[16] The values of the new set of coefficients are $a = -80$ A km/V and $b = 1$ A km/V. The reason for the difference between the value of b derived by Koen [2002] and us is not perfectly clear. One possible reason is that the non-1-D nature of the true conductivity structure is partially captured by the coefficients derived by us. Whatever the reason for the difference is, the fact remains that the coefficients that we derived give much better data-model agreement. The new coefficients were then used as input parameters to the ground model derivation. The first 12 h of the data set was excluded in both network coefficients and conductivity model derivation and reserved for the model validation process carried out in section 5. Figure 2 shows the variations involving the geomagnetic field rate of change dX/dt and dY/dt components and the GIC for the storm events of 29–31 October 2003.

4. Layered Earth Conductivity Model

[17] First, by applying the methods developed by Pulkkinen *et al.* [2007], we used 1-min geomagnetic field and GIC data and the new network coefficients to derive the surface impedance. The apparent resistivities and the phases computed from the derived surface impedance are presented in Figure 3. It is established from Figure 3 that despite the very limited amount of data available to us, a relatively good estimate of the surface impedance is obtained up to a period of about 7000 s. Then, the derived surface impedance was utilized in the simplified Occam's inversion algorithm used by Pulkkinen *et al.* [2007] to

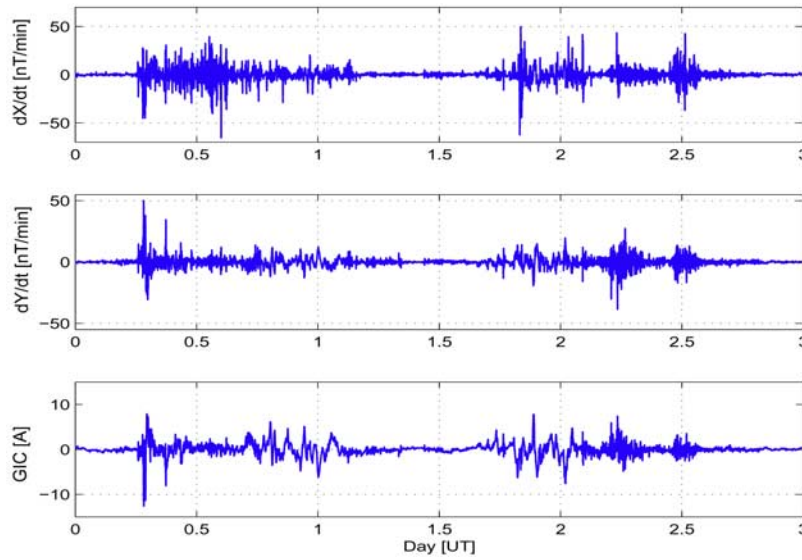


Figure 2. Comparison of the horizontal geomagnetic field rate of change dX/dt and dY/dt components to the measured GIC for the storm events of 29–31 October 2003.

derive a 1-D 10-layer ground conductivity model (hereafter called layered ground model). The number of layers was chosen to minimize the complexity of the model while still capturing the central features in the vertical variations of the conductivity. The resulting conductivity model is introduced in Figure 4 and the corresponding model apparent resistivities and phases agree quite well with the values obtained from the derived surface impedance, as seen in Figure 3.

[18] It is important to note that although the layered ground model in Figure 4 reflects the geological condi-

tions of the region, it is not likely to be a very good characterization of the true conductivity (and geological) structure of the region. More specifically, it is known that the true conductivity structure of Southern Africa has strong lateral gradients rendering the ground very non-1-D [Hamilton *et al.*, 2006; Weckmann *et al.*, 2007]. Thus, for example, the well-conducting layer at a depth of about 200 km seen in Figure 4 may be due to non-1-D effects rather than due to a true conductor in the lower crust or upper mantle [see, e.g., Constable, 1985]. Since the goal of our work is not geological interpretation of the data, but

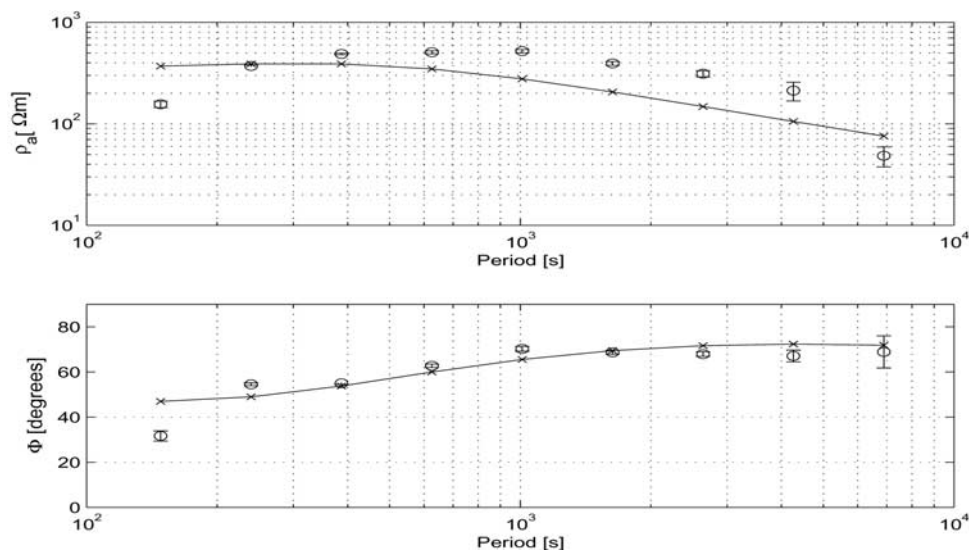


Figure 3. The (top) apparent resistivity and the (bottom) phase computed from the derived surface impedance (circles) and of the derived conductivity model (crosses).

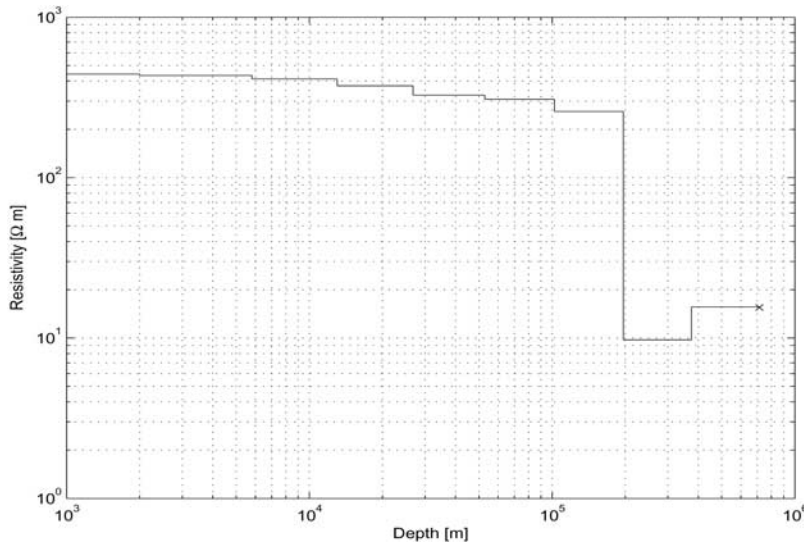


Figure 4. Ground conductivity model derived from the surface impedance. The cross denotes the resistivity of the terminating half-space.

the generation of an optimal model for the modeling of GIC events, any possible ambiguity associated with the interpretation of the derived 1-D conductivity model is not important. One should, however, note that because of the non-1-D character of the true ground, the layered ground model is likely to be valid only for the used specific geomagnetic observatory and GIC station pair and should not be applied blindly to other situations.

5. Improving the Modeling of GICs

[19] The geoelectric field was modeled by the plane wave method using Hermanus magnetic field data and the layered ground conductivity model. The model GIC was computed first by using the uniform ground model and network coefficients of Koen [2002] and second by using the layered ground model and new network coefficients. The validity of the layered ground model and new network coefficients was then tested by making a comparison of the two model GIC computations to the measured GIC for the Halloween storm event of 29 October 2003. The data for the first 12 h of October 29, which were not used in the model derivation process, were utilized in this test and the results are shown in Figure 5. Clearly, the layered ground model and new network coefficients produce a much more accurate representation of the event. Particularly notable from Figure 5 is the gross overestimate of the peaks between the hours 0600–0700 and 0700–0800 UT for the uniform model.

[20] We determined the difference between the measured and modeled GIC and derived the error distribution given in Figure 6. The distribution shows that the layered model and new network coefficients effectively reduce the number of large errors. Then, we determine relative errors defined as $(\text{GIC}_{\text{measured}} - \text{GIC}_{\text{modeled}})/\text{GIC}_{\text{measured}}$ for

values corresponding to $|\text{GIC}_{\text{measured}}| > 1$ A. The median error for the layered model is 48% while that for the uniform layer model is 82%. We also determine the root mean square deviation (RMSD) for the two models, which is defined as $\text{RMSD} = (\sum_{i=1}^n (\text{GIC}_{\text{measured},i} - \text{GIC}_{\text{modeled},i})^2/n)^{1/2}$. The RMSD method is used to compare the deviation of two models with respect to the measured data set. This is achieved by aggregating the individual differences into a single measure of predictive power, with positive values close to zero indicating accurately modeled GIC. The layered ground model and new network coefficients show a good improvement with a RMSD value of 1.56 compared to the value of 3.49 found for the model with uniform ground.

6. Discussion and Conclusions

[21] By extending the grid, Southern African power companies are trying to ensure that the needs of our society are met. However, this network expansion program increases vulnerability to the potential effects of GICs which build up cumulatively over large geographic scales, and may overwhelm protection margins of equipment and the capacity of the system to regulate voltage, leading to power blackouts.

[22] Network coefficients are critical in the modeling of GIC events. The method used here to modify the network coefficients is very simple and circumvents the complex process associated with full GIC modeling of the system that would require knowledge about the network parameters of the entire power grid. Further, the layered ground model is seen to improve the accuracy of GIC modeling. To get more reliable results would require additional GIC data. We argue that the layered ground model could perform much better than the 48% relative error found

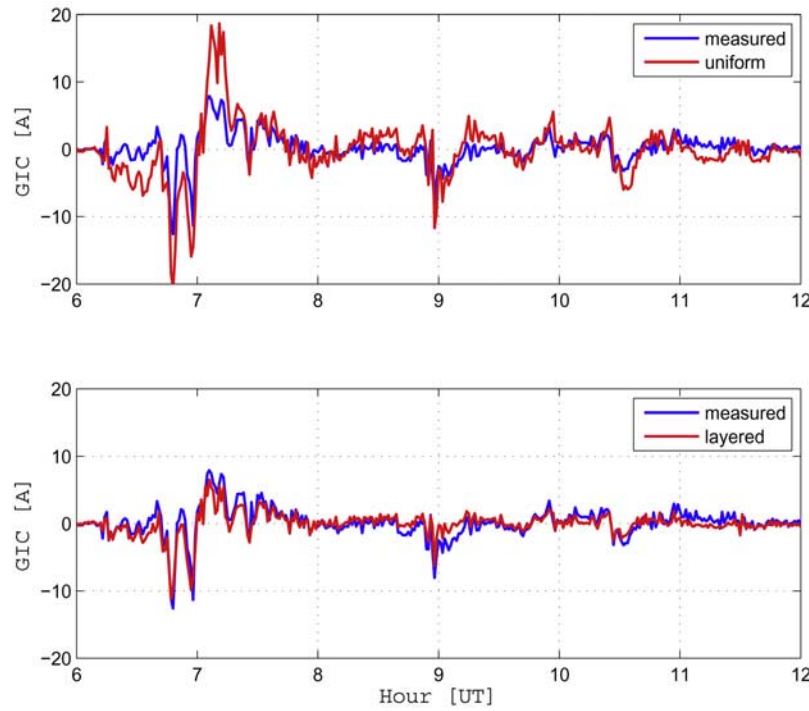


Figure 5. A comparison of the modeled GIC with the measured GIC using two different ground models and network coefficient sets for the Halloween storm of 29 October 2003. (top) GIC modeled using network coefficients and uniform ground model by *Koen* [2002]. (bottom) GIC modeled using new layered model and new network coefficients. The interval used was not included in the derivation of the new network coefficients or the layered conductivity model.

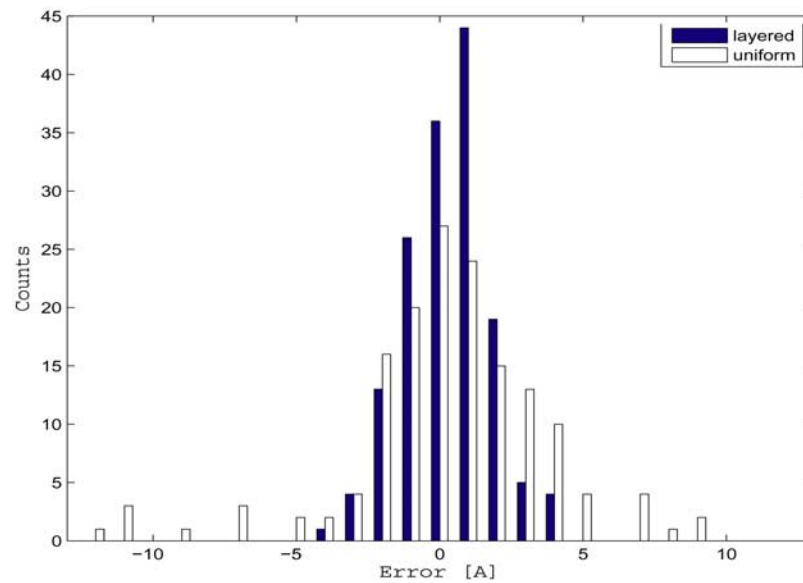


Figure 6. Error distribution defined by $(GIC_{\text{measured}} - GIC_{\text{modeled}})$. White bars show distribution of GIC modeled using network coefficients and ground model by *Koen* [2002] and blue bars show the distribution of GIC modeled using layered ground model and new network coefficients. A bin width of 1 A was used.

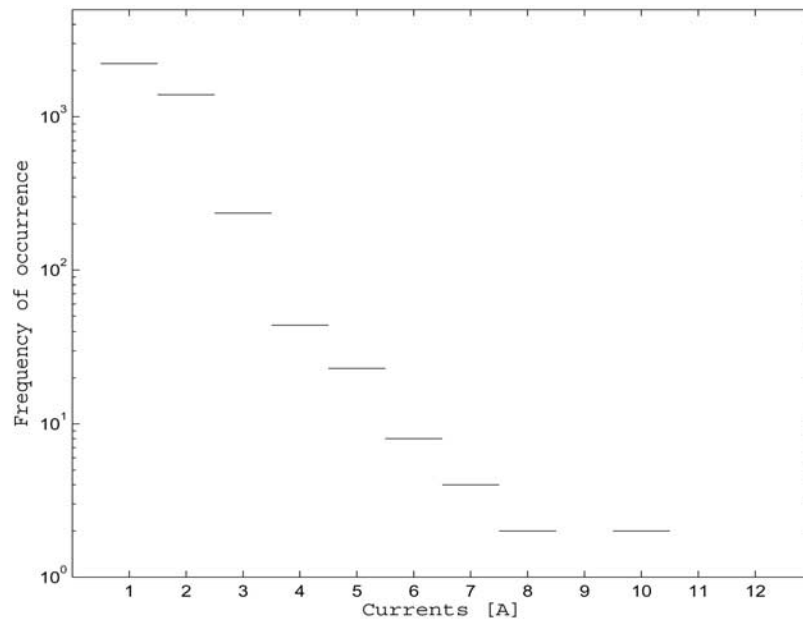


Figure 7. GIC statistics for the period 1996–2006 based on absolute model GIC magnitude >1 A.

in the analysis, if a larger data set would be available for the derivation process. *Pulkkinen et al.* [2007] used a sample space with 8 days data and their results yielded a relative error of 35%. It is worth noting that the layered ground model does not take account any lateral variations in the conductivity structure which are important, for example at continental ocean boundaries. Southern Africa is known to have electrical ground conductivity anomalies [see, e.g., *Constable*, 1985; *Hamilton et al.*, 2006; *Weckmann et al.*, 2007] and thus this ground model is only applicable to the Grassridge station until further studies on conductivity structures are carried out at other sites.

[23] On the basis of the layered ground model, the new network coefficients and geomagnetic field measurements from Hermanus, we modeled the GICs for 86 geomagnetic storm events, assuming that the network is the same as used in the surface impedance derivation during the period 1996–2006. Then a statistical estimation of the occurrence of $|GIC| > 1$ A in the power system was conducted and the results are presented in Figure 7. The currents seen here are much smaller than those observed at higher latitudes like in Finland, where currents as high as 57 A were measured during the October 2003 events but with no reported transformer failures [e.g., *Viljanen et al.*, 2006]. The largest absolute model GIC value within our period of interest was 11.9 A, which occurred during the 29 October 2003 geomagnetic storm, while the largest measured GIC value for the same storm was 12.6 A. Considering the level of currents observed in Figure 7, it is clear that the South African network is at risk. To experience transformer failures, even at such low GIC amplitudes could probably be related to the design of the transform-

ers and to the design of the power system as a whole. There is, therefore, a need to carry out an investigation to determine which of the two cases is more responsible for the failures.

[24] In conclusion, it is important to stress that GIC studies within the midlatitude Southern Africa region are hampered by the lack of measured GIC data. There are only two GIC monitoring sites known to the authors. The situation is aggravated by the very small number of magnetic observatories covering this vast region. This makes it challenging to model and determine the impact of GIC events on the network. However, transformer failures experienced at substations on the South African and Namibia networks show that there exists a strong necessity to improve the modeling efficiency.

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